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Optimization of Wind Farm Regular Layout Based on Grid Coordinate Genetic Algorithm

Huang Guoqing[1)], *Sai Zhang[2)] and Ke Li[3)]

[1)], [2)], [3)] *School of Civil Engineering, Chongqing University, China*
[2)] 202016021042@cqu.edu.cn

ABSTRACT

At present, the optimized layouts given in the research of wind farm layout optimization are mostly disordered, which can hardly meet the requirements of wind farm installation companies for the orderly arrangement of wind turbines. Therefore, this paper proposes a wind farm layout optimization method based on grid coordinate genetic algorithm, which makes a row of wind turbines move back and forth, and a column of wind turbines move left and right, so as to adjust the layout of wind farms, solve the problem of scattered layout of wind turbines, and to improve output power. Using this optimization method, the present study, based on "Ishihara Gaussian Wake Model" and “Jensen Wake Model”, optimizes wind farm arrangement under three different wind conditions in a 2km×2km classic wind farm area, and then compares the optimization effects of the two models. The results show that, under three wind conditions, the optimization based on "Ishihara Gaussian Wake Model" increases power by about 1%, while the "Jensen Wake Model" increases power by more than 2%, higher than the "Gaussian Wake Model" scheme, but the overall optimization effect is not as good as the former because of its serious error and low accuracy in wind speed estimation.

1. INTRODUCTION

With the exhaustion of mainstream energy such as oil and natural gas, people pay more and more attention to the development of renewable energy. Among them, wind energy has become an ideal substitute for fossil fuels because of its high conversion rate, cleanness and safety. In order to collect and utilize wind energy, various wind farms have been set up all over the world. According to the report of World Wind Energy Association (WWEA), the installed capacity of wind power increasing year by year. In 2020, the installed capacity has increased by 93GW, and reached 744GW in total, enough to meet 7% of the global electricity demand. However, due to the influence of wake effect, the wind speed of the downstream turbine drops sharply, and the power output suffers serious losses. Research shows that the influence of wake on the actual wind turbines can reduce power output of wind farms by 15%-50% (Tian 2014). Therefore, as one of the most challenging problems, the layout optimization of wind farms has attracted more and more attention. The existing research on wind farm layout optimization can be categorized into two types: (1) Algorithm research in layout optimization; (2) Research on constraint conditions of wind turbine arrangement in layout optimization (Feng et al. 2020).

Optimization algorithm is vital for wind farm layout optimization, and abundant studies have been conducted. Different algorithms have been utilized to optimize the layout of wind turbines, including Monte Carlo simulation method, simulated annealing algorithm, evolutionary algorithm, particle swarm optimization algorithm, ant colony algorithm, multi-objective genetic algorithm, and some others. Among them, Grigorios Marmidis et al. (Marmidis et al. 2008) introduced Monte Carlo simulation method, and optimized the layout, with maximum output power and minimum installation cost as the criteria; Martin Bilbao et al. (2009) designed a simulated annealing algorithm to explore the layout of wind turbines that can maximize the annual profit of wind farms; Javier Serrano Gonzalez et al. (2010) proposed an evolutionary algorithm to optimize the layout of wind farms and verified its performance; Souma Chowdhury et al. (2012) established an unrestricted wind farm layout optimization model and adopted particle swarm optimization (PSO) to optimize the layout of wind farms; Yunus Eroglu et al. (2012) proposed ant colony algorithm to maximize power output; S.D.O. Turner et al. (2014) applied mathematical programming method to wind farm layout optimization; Sedat Sisbot et al. (2010) adopted multi-objective genetic algorithm to optimize the layout of wind turbines installed on Gokceada Island in the northern Aegean Sea; Qingshan Yang et al. (2018) improved the genetic algorithm and used it to optimize the layout of wind farms.

In the research on constraint conditions of wind turbine arrangement in wind farm layout optimization, Mosetti (1994) was the first to combine the wind farm model based on wake and genetic algorithm, and divided a 2km×2km rectangular wind farm into 10×10 grids. Each grid was a potential installation location, and wind turbines were randomly arranged in the wind farm. If the grid was equipped with a wind turbine, the value was 1, otherwise it was 0. The wind farm layout was represented by 100 binary strings of 0-1, and it was optimized by genetic operations such as selection, crossover and mutation; Grady et al. (2005) increased the population number and iteration times on the basis of Mosetti, and got a better solution; Chunqiu Wan (2009) adjusted the coordinates of the wind turbines in each grid according to the optimization results of Grady, so as to optimize the power output of the whole wind farm.

To sum up, the pioneering scholars have made fruitful theoretical research and practical exploration into wind farm layout optimization, gained in-depth knowledge on optimization algorithm and constraints of wind turbine arrangement, formed important academic achievements, and laid a good foundation for follow-up research. At the same time, we also notice that most of the wind turbine layouts obtained in the existing optimization studies are scattered, and it is difficult to meet the regular arrangement requirements of wind farm layout. For example, in the grid-based wind farm layout optimization proposed by Mosetti and Grady, the wind turbines can only be placed in the grid center, and the constraints on the location of the wind turbines are too high, so that the space of the wind farm cannot be fully utilized. Furthermore, in Chunqiu Wan's study, the optimized wind turbines are arranged too chaotically, which does not meet the requirements for the neat layout of wind turbines in actual installation. In fact, in many famous wind farms, wind turbines are installed in ways to meet demands with neat arrangement, such as Princess Amalia Wind Farm in the Netherlands and Horn Rev Wind Farm in Denmark, etc., which shows the necessity of neat arrangement of wind farms.

In view of this, the present study proposes a wind farm layout optimization method based on grid coordinate genetic algorithm, which adjusts and optimizes the layout by adopting a real-coded genetic algorithm, so that a row of wind turbines in the unit move back and forth, and a column of turbines move left and right. The method optimizes the layout of wind turbines, solves the problem of scattered layout, and improves output power. Specifically, the three-dimensional Ishihara Gaussian Wake is used to calculate the wake effect and wind speed loss between wind turbines, which is brought into the objective function, and then the genetic algorithm is used to optimize and iterate it, so as to explore the layout of the wind farm with maximum power output. In addition, since the three classic examples of layout optimization proposed by Grady and Mosetti have been fully recognized and widely utilized, the present study takes Grady's optimized layout as the original layout, and explores the layout optimization under the same three wind conditions. The major innovation lies in making a row and a column of wind turbines move back and forth, left and right at the same time, adjusting the layout of wind farms, and realizing the layout optimization.

The first section of this paper summarizes the existing research on wind farm layout optimization, analyzes its limitations, and puts forward the innovation point of the present study. Section Two briefly introduces the wake model and superposition model widely used in wind farm layout optimization; Section Three is the introduction to the optimization methods adopted in the present study; Section Four is the case analysis of the research work; The last section jumps to the research conclusion and summarizes the present study.

2. WAKE MODEL

In this study, the optimization process mainly takes Grady's wind farm layout as the original arrangement, calculates the wind speed of each wind turbine and brings it into the objective function to be optimized, and then iterates through genetic algorithm to obtain the optimal layout. At present, there are mainly two types of methods to study the influence of the tail flow and the wind speed deficit of wind turbines. The first type is the analytical model (the wake model) derived from empirical correlation and fluid dynamics; The second type includes methods based on large eddy simulation (LES) and Reynolds average (RANS) (Parada 2017). In contrast, the first type of method has the advantages of low calculation cost and easy embedding in optimization algorithm, and is widely used in wind farm optimization research and practice. Therefore, this study uses the wake model to calculate wake effect and wind speed loss between wind turbines.

Jensen Wake Model (Jensen 1983) is widely used in wind farm optimization research. It is based on the assumption of momentum conservation in wake region, and there is an initial wake radius behind the turbine, which increases linearly with the downstream distance. The model assumes that the wake expands linearly, which only considers mass conservation, underestimates the velocity loss in the wake center, and overestimates that outside the wake. Therefore, the present study adopts the three-dimensional wake model based on Gaussian distribution, proposed by Takeshi Ishihara (2018), which is based on the assumption of axial symmetry and self-phase of wake loss. The new Gaussian-based analytical wake model is more accurate than Jensen Wake Model in predicting wind speed loss in wake-affected areas, and has universal applicability in both near and far wake areas. At the downstream x_d of wake region, the velocity deficit at a certain point is:

$$\frac{\Delta U}{U_h} = F(C_T, I_a, x_d/D)\phi(r_d/\sigma) \quad (1)$$

$$F(C_T, I_a, x_d/D) = \frac{1}{(a+b\cdot x_d/D+c(1+x_d/D)^{-2})^2} \quad (2)$$

$$\phi\left(\frac{r_d}{\sigma}\right) = exp\left(-\frac{r_d^2}{2\sigma^2}\right) \quad (3)$$

$$r_d = \sqrt{y^2 + (z-h)^2} \quad (4)$$

$$\sigma/D = k^* x/D + \varepsilon \quad (5)$$

where $F(C_T, I_a, x_d/D)$ is the stream-wise function representing maximum velocity deficit function at a downstream distance x_d; $\phi(r_d/\sigma)$ is the velocity-deficit distribution function at radial distance r_d; I_a is ambient turbulence intensity; D is the rotor diameter of wind turbine; h is hub height; σ is representative wake width; y is the horizontal distance from the specified point to the hub height; and z is the vertical distance from the specified point to the hub height.
The following parameters are obtained through experiments and data fitting:

$$k^* = 0.11 C_T^{1.07} I_a^{0.20}$$
$$\varepsilon = 0.23 C_T^{-0.25} I_a^{0.17}$$
$$a = 0.93 C_T^{-0.75} I_a^{0.17}$$
$$b = 0.42 C_T^{0.6} I_a^{0.17}$$
$$c = 0.15 C_T^{-0.25} I_a^{-0.7}$$

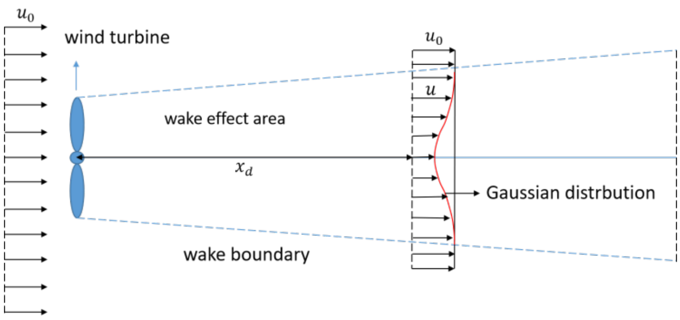


Fig. 1 Schematic of Gaussian wake model

In wind farms, the downstream wind turbines are usually affected by the wake effects of upstream turbines, so it is necessary to calculate the velocity deficit in multi-wake region by using the modified Katic model (1986) which assumes that the total kinetic energy loss is equal to the sum of kinetic energy losses of upstream turbines:

$$u = u_0\left(1 - \sqrt{\sum_{i=1}^{n}\left(1-\frac{u_i}{u_0}\right)^2\sqrt{\frac{A_{overlap}^i}{A_r}}}\right) \quad (6)$$

Where u_i is the wake velocity only affected by *i*th turbine; $A^i_{overlap}$ is the overlap between the *i*th upstream wind turbine wake and the down-stream wind turbine rotor A_r, and n is the number of turbine.

When Jensen Wake Model is used to optimize the layout of wind farms, the influence of the overlap area should be taken into consideration. In this study, when calculating the wind speed, the wind speed of the whole wind rotor is integrated, including the wind speed in the area not affected by the wake. Therefore, the wake velocity in multi-wake region of the present study is:

$$u = u_0\left(1 - \sqrt{\sum_{i=1}^{n}\left(1 - \frac{u_i}{u_0}\right)^2}\right) \tag{7}$$

3. OPTIMIZATION METHOD

Based on the optimization results of Grady's grid method, the present study adjusts a row or column of wind turbines, optimizes the layout as well as output power of the wind farm. When the real-coded genetic algorithm is used to optimize the layout of wind farm, the method for adjusting wind turbines' coordinates is shown in Fig. 2. Each row or column of wind turbines move in the grids at the same time. When moving one row, the turbines move back and forth, and the X coordinates remain unchanged, while the Y coordinates increase or decrease randomly. When moving one column, the wind turbines move left and right, the Y coordinates remain unchanged, and the X coordinates change at the same time.

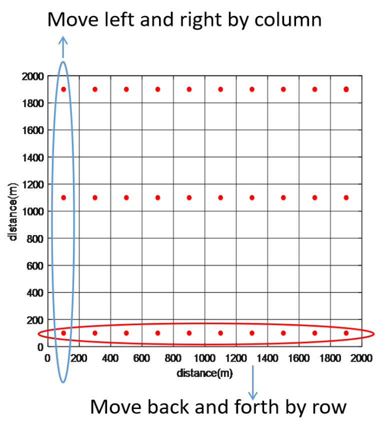


Fig. 2 Schematic of wind turbine position adjustment

3.1 Genetic algorithm

Genetic algorithm is the most commonly used optimization method in the existing research on wind farm layout optimization. Genetic algorithm is a probabilistic search algorithm that combines natural selection and survival of the fittest, and can effectively find the best solution to complex problems. The algorithm does not require the existence of the derivative function of the objective function, and it is robust and global (Grady et al. 2005). According to Grady's optimized layout, the initial population is randomly generated, and the objective function is used as the fitness function to calculate the individual fitness. Based upon Roulette Principle, the individuals with better fitness are retained for the next iteration calculation. The population is updated and iterated through selection, crossover and mutation, the iteration process is shown in Fig. 3.

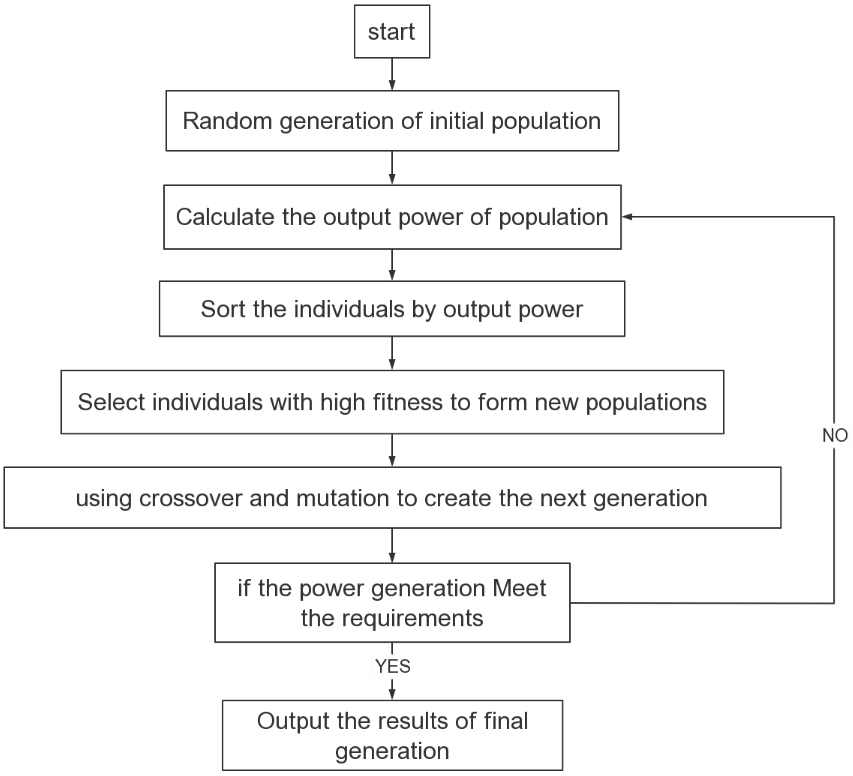


Fig. 3 Schematic diagram of genetic algorithm

3.2 Real-coded

Among genetic algorithms, binary-coded is the most widely used coding method, where each chromosome is a binary string consisting of 0 and 1. For this optimization problem, the variable is too lengthy, the computational domain is too large, which increases the workload. Therefore, the present study adopts real-coded to represent the optimization variables, which overcomes the deficiency of binary coding and improves the efficiency and accuracy of the algorithm. In this study, the optimization variables are the Cartesian coordinates of the wind turbines in the wind farm.

In the present study, each individual to be optimized is represented by a string composed of real values, as shown in Fig. 4, where （x_i, y_i） is the real-coded GA of *i*th turbine.

x_1	$\cdots$	x_i	$\cdots$	x_N	y_1	$\cdots$	y_i	$\cdots$	y_N

Fig. 4 Real-coded method

3.3 Objective function

During optimization, boundary conditions and constraints between wind turbines should be taken into consideration, as shown in Fig. 5:

$$\begin{cases} D_{ij} \geq D_s, i,j = 1,2,\dots,N, i \neq j \\ x_i \in [0,2000] \\ y_i \in [0,2000] \\ \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \geq 1.9D \\ x_i = x_j, ith, jth\ turbines\ in\ the\ same\ column \\ y_i = y_j, ith, jth\ turbines\ in\ the\ same\ row \end{cases} \tag{8}$$

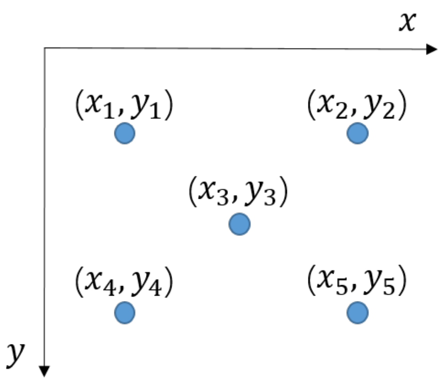


Fig. 5 Wind farm layout

where D_{ij} is the distance between *i*th and *j*th turbines; D_s is the minimum safe distance between wind turbines; x_i is the abscissa of *i*th turbine, and y_i is the ordinate of *i*th turbine.

The objective function of optimization is the total output power of the wind farm, which can be roughly simplified as (Grady 2005):

$$P = \sum_{i=1}^{N} 0.3u_i^3 \tag{9}$$

Where N represents the total number of wind turbines in the wind farm; u_i is the wind speed of the *i*th turbine; *P* is the total power output of the wind farm. The proportion of wake attenuation loss in the wind farm can be expressed by the efficiency of the wind farm as follows (18 Shor-cut design of wind farms) ：

$$\eta = \frac{P}{P_0} \tag{10}$$

where P_0 is the ideal total output power of the wind farm without the influence of tail flow.

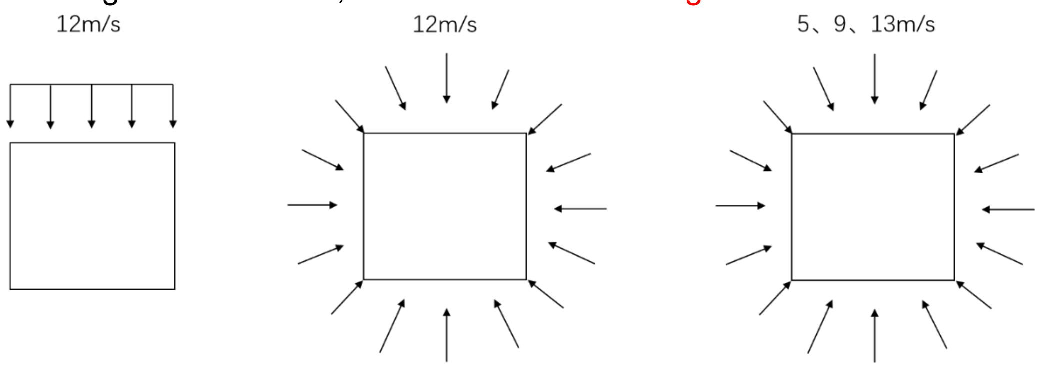
4. CASE STUDY

For a 2km×2km classic wind farm, on the basis of Grady's optimized layout, the present study takes optimal power output into consideration to further optimize the layout, and then compares the optimization result with that based on Jensen Wake Model. Table 1 lists information of the wind turbines and wind field used in this study.

Table 1 Wind turbine parameters

Hub height H	Diameter D	Surface roughness Z_0	Thrust coefficient C_T
60m	40m	0.3	0.88

Case a: constant wind speed and wind direction (12m/s);
Case b: constant wind speed (12m/s) and variable wind direction (36 directions);
Case c: variable wind speed and wind direction (36 directions);
Schematic diagrams of Case a, b and c are shown in Fig. 6.



a. Case a b. Case b c. Case c

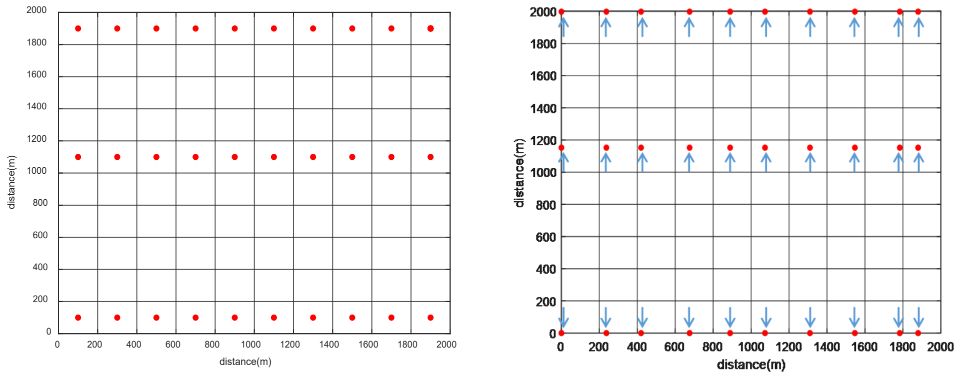
Fig. 6 Wind condition

4.1 Case a: constant wind speed and wind direction

The wind farm includes 30 wind turbines, and the location of the wind turbines is further optimized. See Fig. 7 for the optimized layout and Table 2 for the optimized results. Fig. 7 shows that, in the optimized layout, the wind turbines around the wind farm are offset in the forward and backward directions in rows, and in the left and right directions in columns. The position of the wind turbines in the middle is slightly offset to the downwind.

Table 2 Case a optimization results

	Three dimensional Gaussian wake model		Jensen wake model	
	P(kW)	η(%)	P(kW)	η(%)
Grady's layout	14646	94.17	14297	91.9
present layout	14781	95.04	14497	93.3
Improvement	0.93%		1.4%	



a. Grady's layout b. Present layout

Fig. 7 Wind farm layout (Cace a)

4.2 Case b: constant wind speed and variable wind direction

For complex wind conditions with multiple wind directions, Cartesian coordinate transformation is required. The wind direction angle in case a is set to 0°, and when the wind direction angle between the incoming wind and the wind turbine is θ, the coordinates of *i*th turbine relative to the wind direction angle θ are calculated by Eq. (11) (Parada 2017) ：

$$(X_i, Y_i) = (x_i, y_i) \cdot \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \tag{11}$$

where: (x_i, y_i) is the coordinates of the original *i*th turbine.

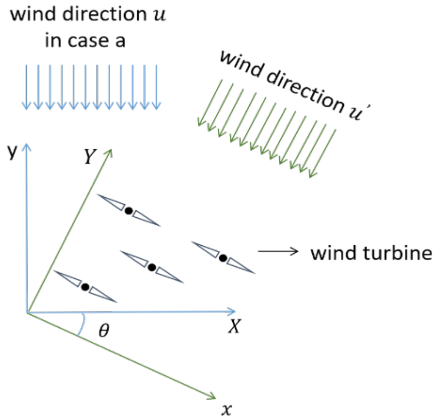
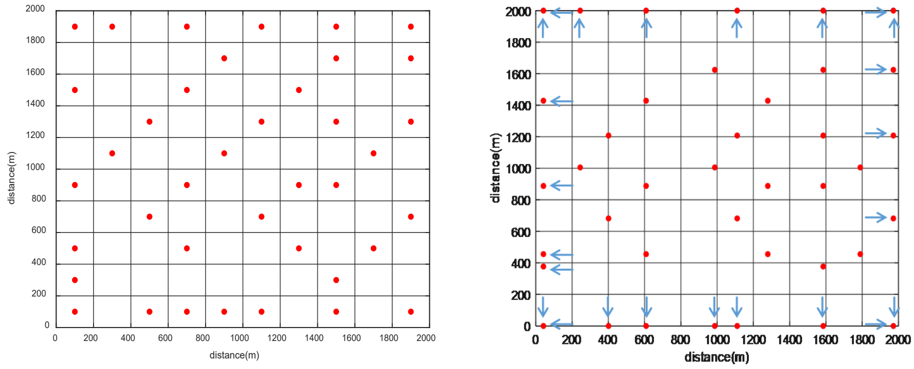


Fig. 8 Schematic diagram of coordinate conversion

On this basis, the follow-up optimization work is carried out. The wind farm includes 39 wind turbines, and the optimized layout and results are shown in Fig. 9 and Table 3 respectively. As can be seen from Fig. 9, in the optimized layout, the wind turbines around the wind farm are scattered to the boundary of the wind farm, which increases the distance between the peripheral wind turbines and the internal ones, and the turbines are offset to the left and right directions of the X axis in columns, thus reducing the wake effect between the wind turbines.



a. Grady's layout b. Present layout

Fig. 9 Wind farm layout (Case b)

Table 3 Case b optimization results

	Three dimensional Gaussian wake model		Jensen wake model	
	P(kW)	η(%)	P(kW)	η(%)
Grady's layout	18551	91.76	16949	83.83
present layout	18723	92.61	17415	86.14
Improvement	0.92%		2.7%	

4.3 Case c: variable wind speed and wind direction

In classic wind farms, the wind speed in Case c was relatively high, reaching 14m/s, which was quite different from the actual wind conditions. Therefore, the probability distribution of wind speed and direction was improved in the present study. The improved wind speed distribution is more consistent with the wind conditions of the actual wind field, and the average wind speed is about 7.5m/s. The improved probability distribution of wind speed and direction is shown in Fig. 10. The layout of the classic wind farm is optimized in Case c. See Fig. 11 for the optimized layout and Table 4 for the results. From Fig. 11, it can be seen that the trend of peripheral wind turbines shifting around the wind farm is the same as that of Case b, and more wind turbines are arranged in the wind direction with high probability of wind speed. The results in Table 4 show that the optimization based on Gaussian Wake Model increases the power output by 1.05%, and that based on Jensen Wake Model increases by 2.19%.

From the comparison of the above optimization results, it can be seen that in three Case, the output power increased by 0.9%-1% based on the three-dimensional Gaussian Wake Model, and the output power increased by 1.4% in Case a, and increased by more than 2% in Case b and c based on Jensen Wake Model. From the increase range of output power, the optimization based on Jensen Wake Model is higher than that based on three-dimensional Ishihara Gaussian Wake Model. However, since Jensen Wake Model overestimates wake effect and velocity-deficit, the optimization space seems to be larger, which leads to false improvement of higher power output. The three-dimensional Gaussian Wake Model is more accurate in predicting the velocity-deficit, and the calculated output power is better than that calculated by Jensen model

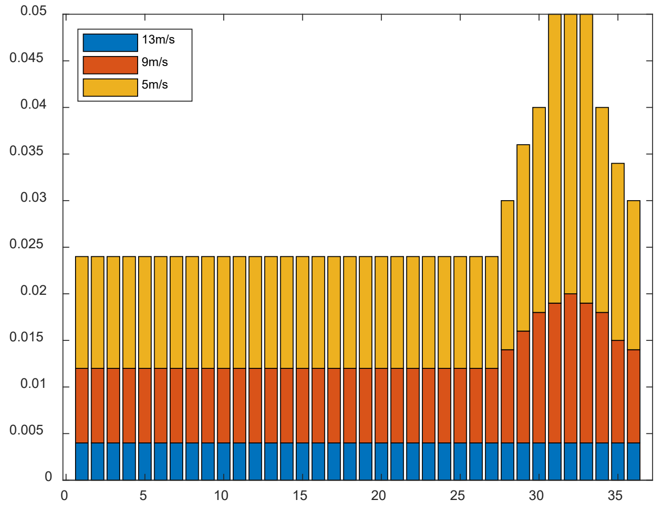
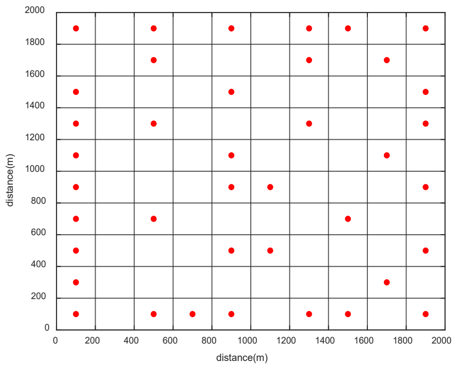
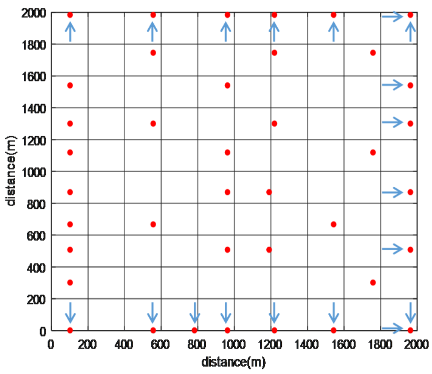


Fig. 10 Probability distribution of wind direction and speed



a. Grady's layout



b. Present layout

Fig. 11 Wind farm layout (Case c)

Table 4 Case c optimization results

	Three dimensional Gaussian wake model		Jensen wake model	
	P(kW)	η(%)	P(kW)	η(%)
Grady's layout	6789	92.77	6024	82.31
present layout	6860	93.74	6156	84.12
Improvement	1.05%		2.19%	

5. CONCLUSION

Based on the "Three-Dimensional Ishihara Gaussian Wake Model", the present study proposes a method to optimize the layout of wind farms by adjusting the coordinates of wind turbines in a row or column at the same time, and increases output power. With the real-coded genetic algorithm as the optimization objective, the optimized layout given by Grady for a 2km×2km classic wind farm under three different wind conditions is re-optimized, which solves the problems of scattered layout in current wind farm layout optimization schemes, which is inconsistent with the neat arrangement requirements of the actual wind farm installation, and improves output power of the wind farm at the same time. This study finds that the increase range of wind output power based upon Jensen Wake Model optimization is obviously higher than that based on Gaussian Wake Model optimization. However, because of its serious error and low accuracy in wind speed estimation, the overall effect of Gaussian Wake Model optimization scheme is better.

The innovation of this study is adjusting the position of one row or column of wind turbines in the wind farm at the same time, optimizing the layout, making it meet the requirements of regular layout, and improving output power. Under three working conditions, the optimized output power increased by about 1%. The effectiveness of the wind turbine layout optimization method proposed in the present study is verified, which provides a new feasible method for wind farm installation layout.

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